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Blast Mitigation Using Water Mist

Jean L. Bailey
John P. Farley
Frederick W. Williams

Navy Technology Center for Safety and Survivability
Chemistry Division

Michael S. Lindsay

Marioff, Inc.
Linthicum, MD

Douglas A. Schwer

Center for Reactive Flow and Dynamical Systems
Lab for Computational Physics and Fluid Dynamics

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*Marioff, Inc., Linthicum, Maryland

14. ABSTRACT

A series of experiments demonstrating the mitigation of water mist on the over-pressure effects of a TNT detonation have been conducted. A series of TNT charges, 0.9 kg (2 lb), 2.2 kg (5 lb) and 3.2 kg (7 lb), were detonated both with and without employing a water mist system. The TNT detonations were characterized by five measurements: initial blast over-pressure start time, peak, and impulse, as well as quasi-static pressure and start time. The initial blast over-pressure peak and impulse, as well as quasi-static pressure were reduced by the presence of water. These experiments show that the use of water mist to mitigate the over-pressure effects of a high explosive detonation is an extremely promising concept.

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BLAST MITIGATION USING WATER MIST

1.0 INTRODUCTION

Water mist has been successfully used to suppress fires and has been documented extensively [1,2]. The use of water mist to mitigate explosions has also been explored and appears very promising [3]. A clarification of terms is necessary before further discussion. The definition of an explosion is the release of energy that causes a rapid increase in gas density, pressure, and velocity as a result of: high explosives (example, TNT), nuclear reaction, loss of containment in high pressure vessel, run-a-way reactions, and combustion of dust, mist, or gas in air or other oxidizer [4]. There are two types of explosions: deflagrations and detonations. A deflagration is a propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at less than sonic velocity in the unreacted material. Whereas, a detonation is a propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic velocity in the unreacted material [3]. The main differences are the speed of the reaction and the fact that detonations are typically much more destructive than deflagrations. Deflagrations as a result of the combustion of gas in air or other oxidizer is the most common type of explosion and is, therefore, the type of explosion most studied in water mist mitigation research. While deflagrations are of concern to the Navy, this work describes experiments using water mist to mitigate the overpressure effects from the detonation of high-energy explosives, namely TNT. These types of explosions are relevant to the Navy not only in wartime, but also in peacetime scenarios, such as accidents (munitions storage) as well as terrorists' threats.

2.0 BACKGROUND

TNO Prins Maurits Laboratory, a semi-government laboratory in the Netherlands, performed experimental research in the area of explosion suppression. A brief summary appeared on their website: "Several experiments by TNO Prins Maurtis Laboratory, some of which in cooperation with NATO partner Germany, have demonstrated considerable explosion pressure reduction (by tens of percents) with active explosion suppression systems. The heart of each system is plain water mist." [5]. Subsequent communication via email with Mr. A.G. van Erkel revealed that they "did many experiments up to 5 kg HE (high explosive) with water bags, water mist, injected water, etc. [6]." Further details are unknown, although current efforts include working with the technical project officers in charge of the Data Exchange Agreements with both the Dutch and German governments. The relevant point of this experimental program was that plain water mist was used to successfully mitigate explosions caused by high explosives.

Theoretical research into blast mitigation using water mist includes work performed by Dr. D. Schwer and Dr. K. Kailasanath [7, 8]. Preliminary simulations have shown that water mist could significantly reduce the quasi-static pressure of a 2.2 kg (5 lbs) TNT explosion.

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3.0 OBJECTIVES

There were two objectives for this test series. The first was to quantify the effectiveness of water mist in mitigating the initial blast overpressures and quasi-static pressures associated with detonations. The second objective was to provide experimental data for comparison with model simulations.

4.0 BOMBPROOF CHAMBER

A plan view, illustrating the shape of the bombproof chamber, is given below in Figure 1. The chamber was located at the Naval Surface Warfare Center (NSWC), Indian Head Division. The inside dimensions of the chamber were 4.6 m x 4.6 m x 3.1 m (15.1 ft x 15.1 ft x 10.1 ft). The interior walls were 0.9 m (3.1 ft) thick reinforced concrete lined with a 2.4 cm (1 in) thick steel plate. Both a supply and exhaust pipe protruded down from the ceiling into the chamber. The positions and sizes are shown in a scale drawing (Figure 2).

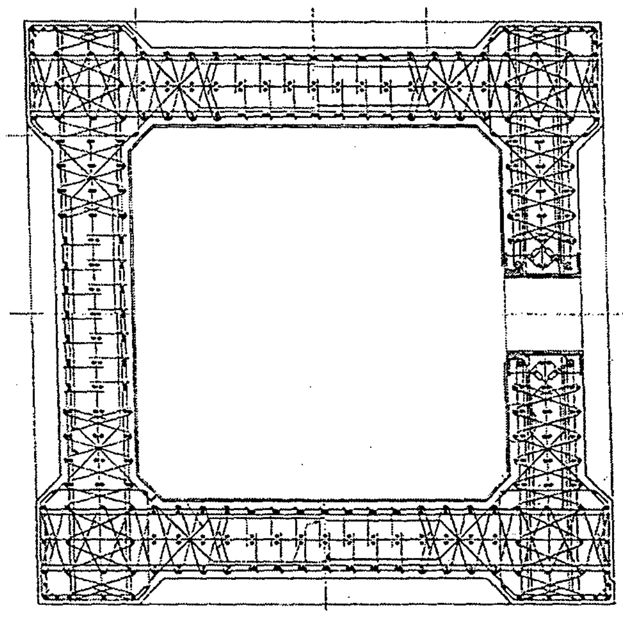

Figure 1. Plan view of bombproof chamber.

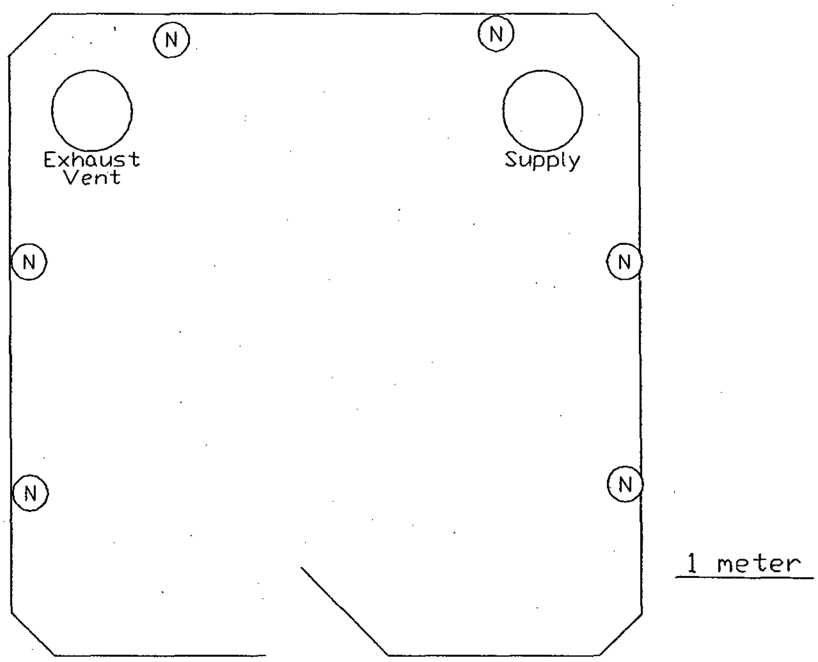

Figure 2. Scale drawing of bombproof chamber showing vent and nozzle placement.

5.0 WATER MIST SYSTEM

Figure 2 is a scale drawing of the bombproof chamber which gives exact locations of the six water mist nozzles inside the bombproof chamber. The nozzles are denoted by circles with the letter "N" inside. The nozzles were located 1.6 m (64 in) above the floor. Figures 3 and 4 are photographs of the water mist system inside and outside of the bombproof chamber, respectively. Figure 5 shows a schematic of the system including instrumentation. The instrumentation is discussed in Section 6.0.

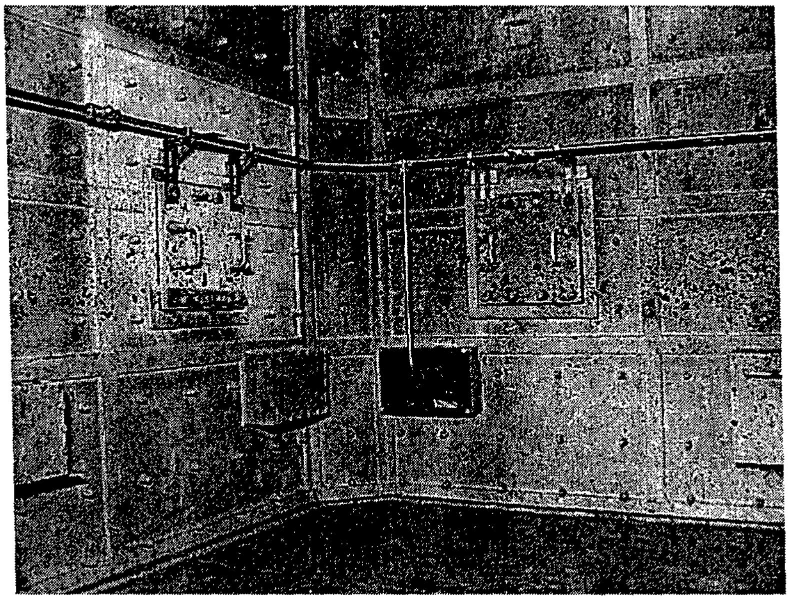

Figure 3. Water mist system inside bombproof chamber.

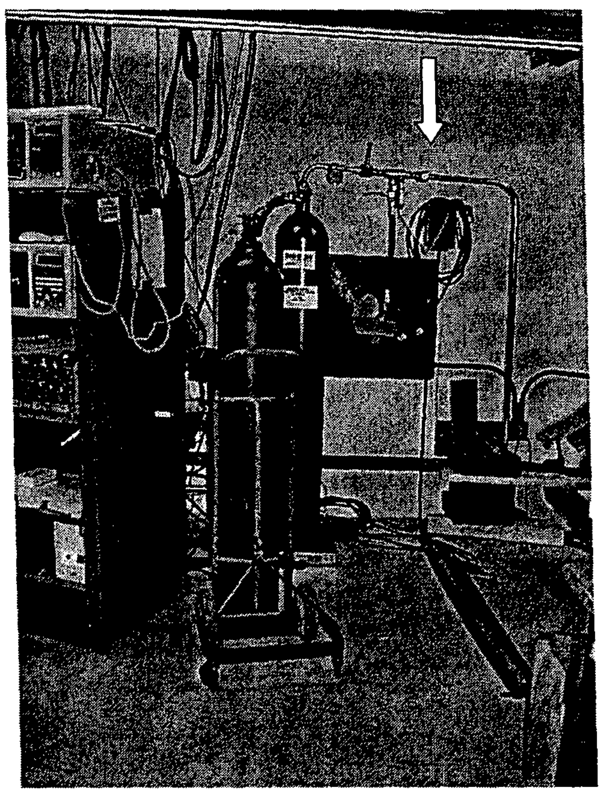

Figure 4. Water mist system outside bombproof chamber.

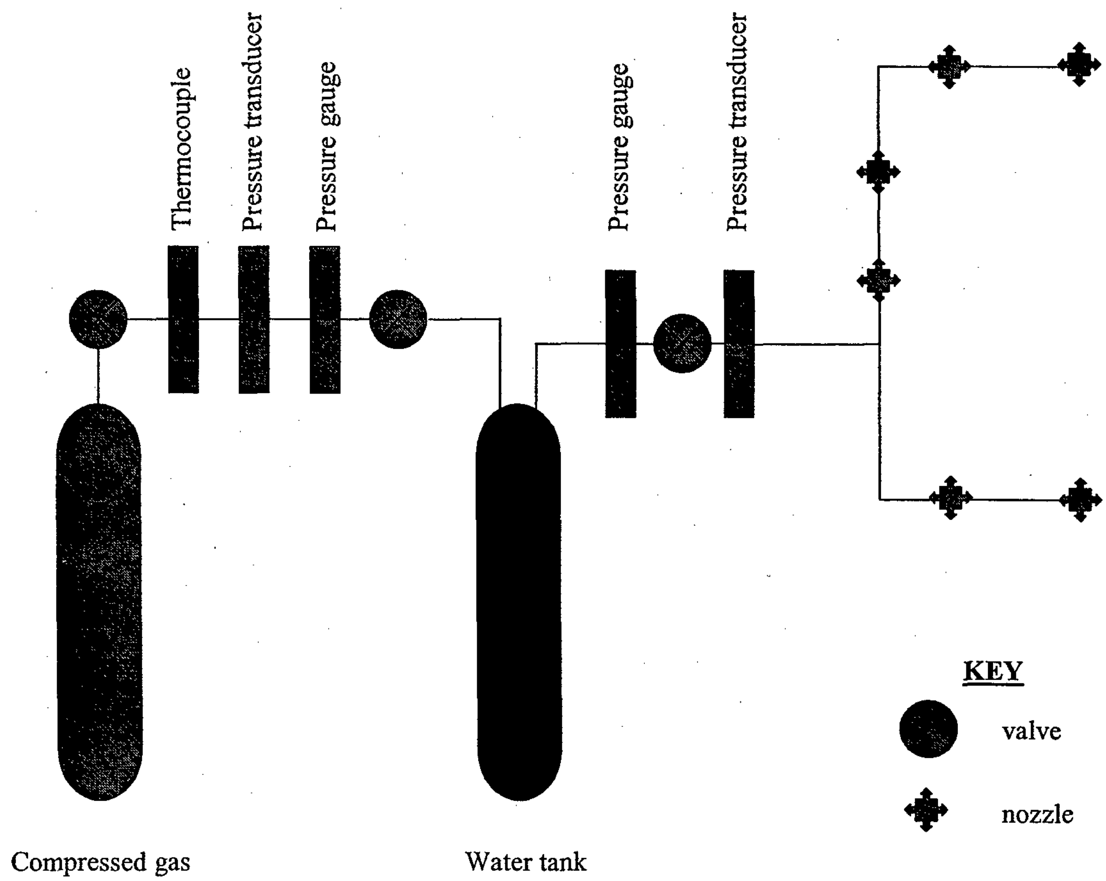

Figure 5. Water mist system schematic.

The water mist system consisted of a 50-liter pressure vessel (water tank) filled with water. The water was tap water filtered through a 5 micron Culligan cartridge (model CUL P5) contained within an American Plumber Model WC34-PR housing. The compressed gas (either nitrogen or air) forced the water out of the tank, through the nozzles, and into the bombproof chamber.

The valve shown in Figure 5 above the compressed gas cylinder is the valve that comes on a standard compressed gas cylinder. There were two ball valves, which allowed for isolation of certain sections of the water mist system so the compressed gas cylinders could be changed and the water tank could be filled. For safety, pressure gauges, which allowed for quick visual readings, were located in each of the sections that could be isolated.

A 48 cm (19 in) flexible hose, 12 mm OD/ 9.6 mm ID, connected the compressed gas cylinder to a distribution block which contained all of the instrumentation between the compressed gas and water tank. This is not visible in Figure 4. The dip tube inside of the water tank was 16 mm OD/ 13 mm ID and made of stainless steel. There was a small hole approximately halfway down the dip tube. This allowed for both compressed gas and water to exit the water tank once the level of the water dropped halfway. Prior to this time, water was the

only fluid exiting the nozzles. Directly downstream of the final pressure transducer, denoted by the white arrow in Figure 4, the stainless steel piping changed to 25 mm OD/ 21 mm ID for the remaining piping outside the bombproof chamber as well as all of the piping inside the bombproof chamber. A ball valve, connected to a black flexible hose and visible directly upstream of the white arrow in Figure 4, was never used and is therefore not shown in the schematic (Figure 5).

The water mist nozzles were Marioff 4S1 MC 8MB 1000. The K-factor for this nozzle is 1.9 $lpm/bar^{0.5}$. These nozzles have 90^{o} spray heads and are constructed of stainless steel. There is one center nozzle that is 1.0 mm in diameter and eight cone nozzles that are 0.7 mm in diameter.

Indian Head personnel fabricated a bracket to attach Marioff water mist system to the chamber wall (Figure 6).

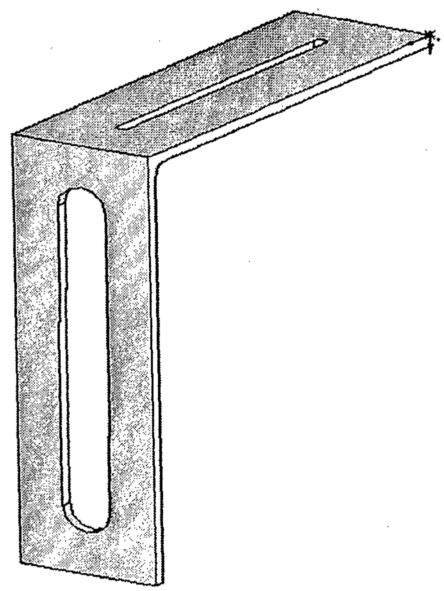

Figure 6. Bracket used to attach water mist piping to bombproof chamber. Drawing provided by Matthew Kennedy, NSWC Indian Head

6.0 INSTRUMENTATION

A scale was used to measure the weight of the water tank. The scale was a Span GCS-300 (0-500 lb). The weight versus time curve was used to verify that the performance of the water

mist system was consistent throughout the test series. It also gave a measure of the amount of water as a function of time that was exiting the nozzles.

A Honeywell Sensotec pressure transducer model Z (0-3000 psig) was located downstream of the compressed gas cylinder. This was used to measure the drop in pressure with time as the compressed gas displaced the water in the tank. The temperature of the compressed gas (air or nitrogen) was measured with a type K thermocouple (Omega part number TJ72-CASS-18U-6) that was located next to the pressure transducer. The pressure and temperature versus time curves were also used to verify the consistency of the water mist system through out the test series. This transducer was protected with a Ray porous snubber model 722SG.

A Honeywell Sensotec pressure transducer model LM (0-3000 psig) was located downstream of the valve which released the water into the chamber. The response of this instrument signaled time zero for the experiments. A Ray piston snubber model 022S, with the #2 piston installed, was used to protect this transducer.

There were three transducers used to measure the pressure at the nozzles. These were located next to the nozzles in Figure 5. The performance of the water mist system was qualified prior to each water mist-suppressed detonation to verify that it was functioning consisting and had not been damaged by a previous detonation. This information also provides valuable information to allow modeling of the nozzles themselves since the quantity and size of water droplets exiting a nozzle is a function of the pressure at the nozzle. This information, in turn, can be used to model the environment inside the chamber at the exact time of detonation. Since there were six nozzles, two tests were done so the pressure at all six nozzles could be measured. Two of the pressure transducers were Honeywell Sensotec pressure transducers model LM (0-3000 psig). The third was a Honeywell pressure transducer model Z (0-3000 psig). All three of these pressure transducers were protected with Ray porous snubbers model 722SE. In Figure 7, the circles labeled 1 and 2 were LM-type transducers and circles labeled 3 were the Z-type transducer. During one of the two tests the transducers were in the position noted as “a” and during the second test, the transducers were in position “b”. Note that the nozzles were located directly adjacent to these pressure transducers, so the transducers were also 1.6 m (64 in) above the floor.

Two Win600e data acquisition systems were used to collect the data. The output of all the transducers mentioned above, as well as the scale, was collected ten times per second. The thermocouple readings were collected five times per second.

There were four high-speed transducers; one in each of the four corners of the chamber. These were Kulite high pressure ruggedized dynamic response IS pressure transducers (HKS-375 M series). The data from these transducers was collected 100,000 times per second. Data was collected for either 1.23 sec or 2.49 sec after detonation, depending on the experiment. Table 1 gives the height of each off of the chamber floor. The designations in the Table refer to the locations of the transducers as shown in Figure 7.

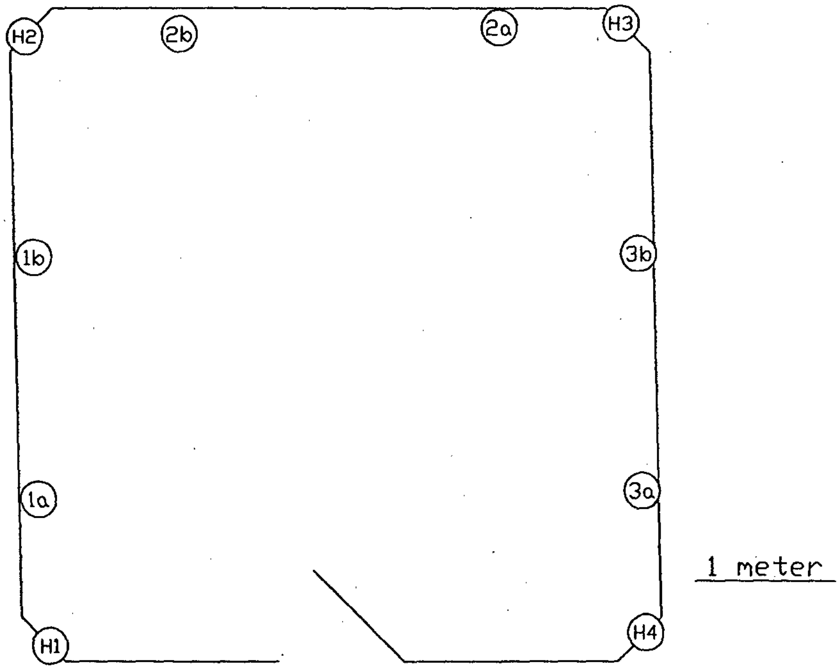

Figure 7. Scale drawing showing location of pressure transducers inside bombproof chamber.

Transducer	Height off floor
H1	1.95 m (76.8 in)
H2	1.96 m (77.0 in)
H3	1.94 m (76.5 in)
H4	2.02 m (79.5 in)

Table 1. Height of pressure transducers H1 through H4 above chamber floor.

7.0 EXPERIMENTAL PROCEDURE

A total of 35 experiments, consisting of four different types, were done. These are listed in Table 2. The information includes date and type of experiment, along with the kind of compressed gas that was used.

Date	Run	Type	Gas
5/26	1	Aa	Air
5/26	2	Ab	Air
5/27	3	Ab	Air
5/27	4	Ab	Air
5/27	5	Ab	Air
5/27	6	Ab	Air
5/27	7	B 2 lbs	Nitrogen
5/27	8	B 2 lbs	No mist
5/31	9	Ca	Air
5/31	10	Cb	Air
5/31	11	B 5 lbs	Nitrogen
5/31	12	B 5 lbs	No mist
6/1	13	Ca	Air
6/1	14	Cb	Air
6/1	15	B 5 lbs	Nitrogen
6/1	16	B 5 lbs	Air
6/1	17	B 5 lbs	No mist
6/3	18	C/Da	Air
6/3	19	C/Da	Air
6/3	20	C/Db	Air
6/6	21	D	Air
6/6	22	D	Nitrogen
6/6	23	D	Air
6/6	24	D	Air
6/6	25	D	Air
6/6	26	D	Air
6/7	27	D	Air
6/7	28	D	Nitrogen
6/7	29	D	Nitrogen
6/7	30	D	Nitrogen
6/7	31	D	Nitrogen
6/7	32	D	Nitrogen
6/7	33	D	Nitrogen
6/8	34	B 7 lbs	Nitrogen
6/8	35	B 7 lbs	No mist

Table 2. Types of experiments run during test series.

The compressed gas, in 300 ft^3 cylinders, was purchased from Airgas for all of the runs except for runs 31, 32, and 33. The nitrogen used in these runs was from an on-site supply. The Airgas nitrogen was industrial grade NI300 and the air was breathing air grade AIB300. The cylinders were nominally 2640 psi at 70 degrees Fahrenheit.

There were four main types of experiments: A, B, C, and D. The small letters "a" and "b" next to these capital letters refers to the position of the transducers as explained in Section 6. The A experiments were essentially shakedowns. It was also during these tests that data was collected to determine how long the water mist system would be allowed to run before the charge was detonated. The B experiments were the detonation experiments. The nozzle transducers were removed for all detonations hence there is no "a" or "b" designations for these runs. The nominal weight in pounds of the TNT charge is also listed. Note also that the nozzles were removed for all of the detonations without mist. The C experiments were done to verify the integrity of the water mist system after the detonation runs. The D experiments were done to characterize the water mist inside the bombproof chamber. A Malvern Spraytec instrument was placed in eleven different positions inside of the chamber. Both droplet size distributions as well as mass loading measurements were taken as a function of time.

Water was vacuumed from chamber floor before each detonation test. The water tank was filled prior to each run and a new full compressed gas cylinder was connected to the water mist system. The water tank was pressurized by opening the cylinder valve and then the first ball valve. Time zero began when the second ball valve was opened. This allowed the pressurized water to flow through the piping, out of the nozzles, and into the bombproof chamber. The 0.9 kg (2 lbs) and 2.2 kg (5 lbs) TNT charges were detonated 30 seconds after the second valve was opened. The 3.2 kg (7 lbs) TNT charges were detonated after 20 seconds. The water mist system was secured a few minutes after the detonation occurred.

7.1 TNT Charge

The length-to-diameter ratio for the cylindrically shaped charges was always one regardless of the size. The center of the TNT charge was always placed in the center of the chamber, 1.5 m (60 in) off the floor. The charge was oriented so the flat ends were parallel to the floor. A detonator was placed on top of the pentolite booster. The booster was placed on top of the TNT charge. Figure 8 shows a photograph of the configured charge inside the bombproof chamber.

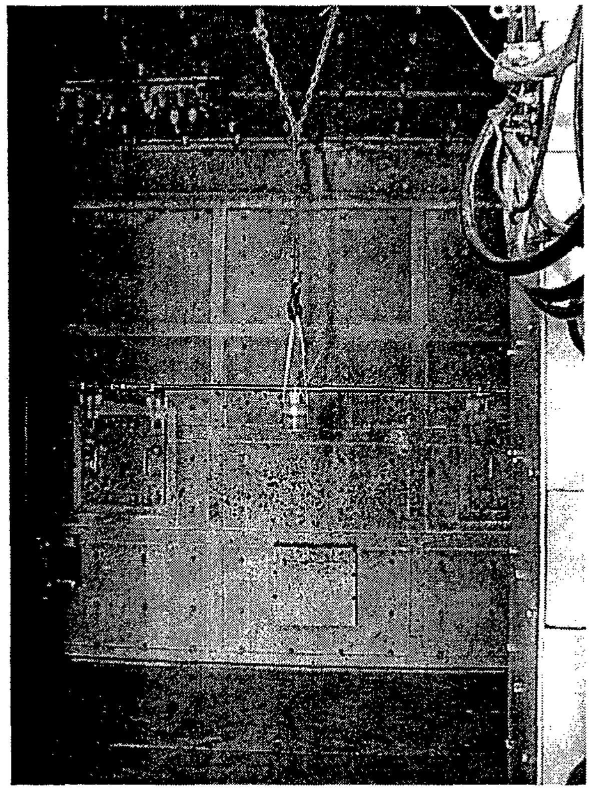

Figure 8. TNT charge inside bombproof chamber.

The amount and sizes of both the TNT and Pentolite boosters are listed in Table 3 according to experiment run number. These numbers correspond to those in Table 2.

	TNT			Pentolite Booster		
Run	Weight (gm)	Diameter (cm)	Length (cm)	Weight (gm)	Diameter (cm)	Length (cm)
7	856.71	8.89	9.02	56.88	3.56	3.63
8	859.41	8.89	8.98	57.21	3.55	3.70
11	2209.0	11.94	12.85	56.80	3.56	3.64
12	2231.5	11.94	13.18	56.72	3.58	3.68
15	2238.0	11.93	12.90	57.32	3.57	3.62
16	2244.2	12.01	12.87	57.04	3.56	3.64
17	2251.4	11.98	12.93	58.17	3.56	3.67
34	3180.7	13.74	13.69	57.63	3.56	3.64
35	3173.6	13.76	13.51	58.09	3.58	3.65

Table 3. Size and weights of charges.

The RP-80 detonator consisted of a mixture of 124 mg of cyclonite (RDX) with plastic binder (PBX 9407) and 80 mg of pentaerythritol tetranitrate (PETN). The Pentolite booster was a mixture of PETN (pentaerythritol tetranitrate) and TNT.

8.0 RESULTS

8.1 Introduction

The four high-speed pressure transducers measured the pressure at four distinct point locations within the bombproof chamber. Each of these transducers generated a pressure trace with time that began before the charge was detonated. Figure 9 is an example of a graph of the raw data from a transducer. There were either 262,143 or 131,071 data points recorded from each transducer during each detonation experiment. The pressure was constantly changing with time. Although graphing these lines next to and on top of each other can be useful, it is very difficult using this method to visualize the effect of the water mist. Instead, for the purpose of data analysis, the pressure traces were sectioned into two regions: the initial blast overpressure and quasi-static regions. Figure 10 shows a portion of the data from Figure 9 corrected for the offset from zero as explained in the next section. The initial blast overpressure region is bracketed by the square symbols. The overpressures in this region are a result of the initial blast wave from the TNT detonation. The pressure returns to near or below zero before the quasi-static pressure region, denoted by the circle symbol in Figure 10, begins. The pressure in the chamber decreases with time and eventually returns to atmospheric. The rate at which this occurs is a function of the vent area within the chamber.

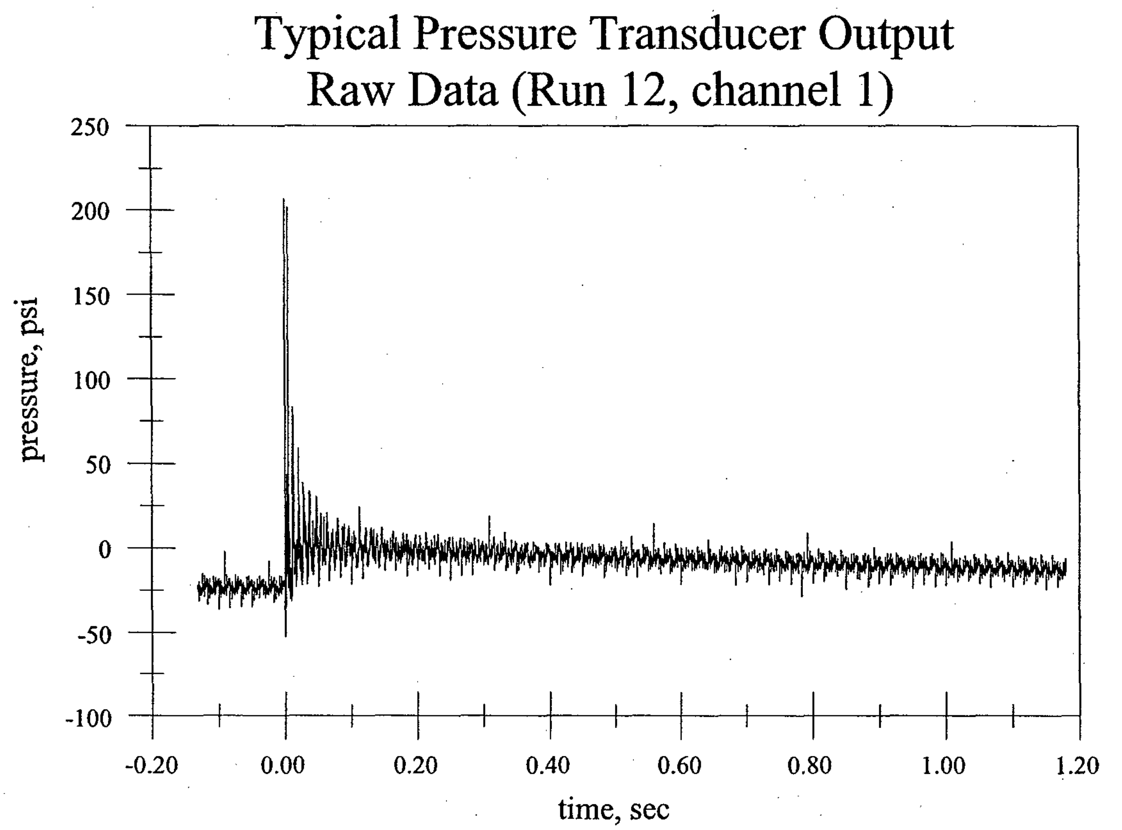

Figure 9. Raw Data from Pressure Transducer; Transducer 1 in Figure 7.

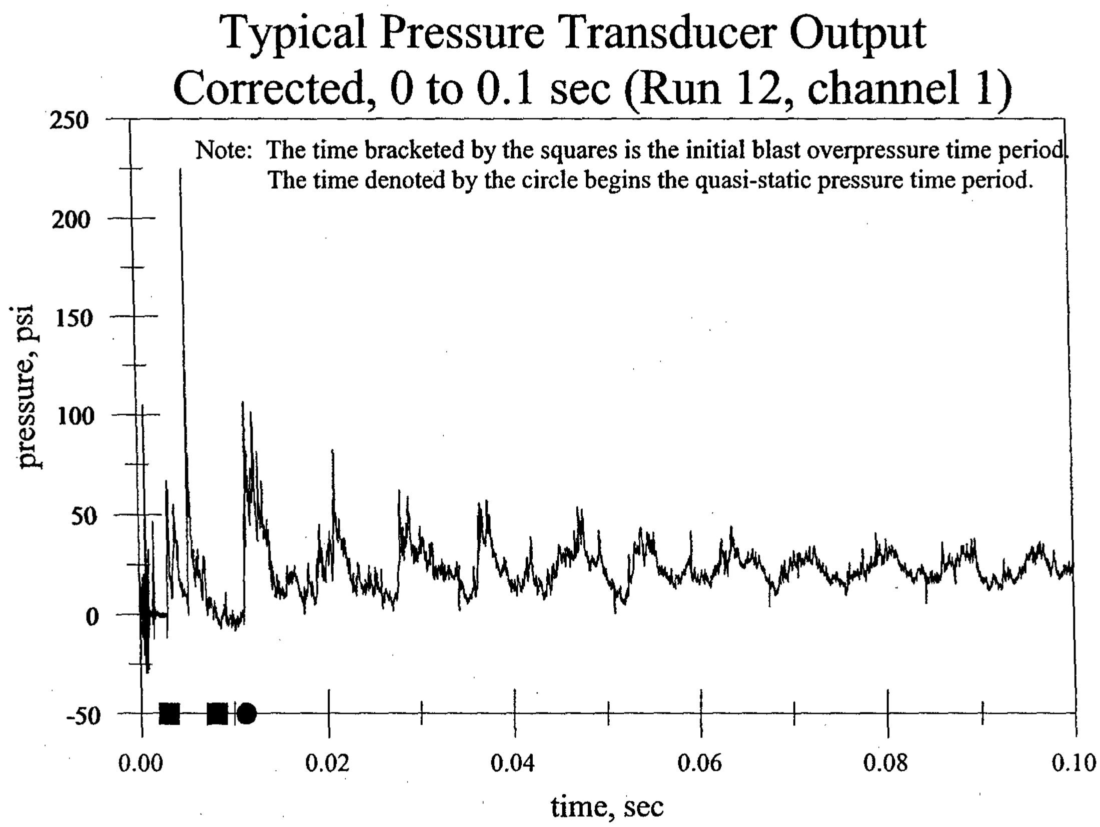

Figure 10. Corrected Pressure Transducer Output; Transducer 1 in Figure 7.

8.2 Data Processing

Data processing begins by averaging the data collected prior to time zero. This is either from –0.13108 sec or –0.08192 sec, depending upon the experiment. This average is then subtracted from or added to the raw transducer output. Note that the pressure transducers are reporting pressure above atmospheric. A reading of zero refers to atmospheric pressure.

Five key results will be shown to quantify the effect of water mist on the TNT detonation. Peak overpressures, impulses, and start times for the initial blast are reported, as well as quasi-static start times and pressure calculations for different time periods. These will be explained in the following sections.

8.2.1 Initial Blast Overpressure

The first of the three quantities investigated within the initial blast overpressure region defined above is the peak overpressure. This is simply the maximum pressure recorded by any of the four corner pressure transducer within the initial blast overpressure time period. Attempting to measure this is very difficult because the pressure waves are extremely non-uniform and fast. In these experiments, the pressure sensors are measuring the pressure at four distinct points within the chamber and the peak pressure lasted no more than one sampling period, i.e. 0.00001 seconds. It is very difficult to get a true measure of the peak pressure during this period. Therefore, both the peak initial blast overpressure as well as the initial blast overpressure impulse is reported. The impulse is an integral of the pressure-time curve. It is a measure of not only how high the pressure got during the initial blast overpressure time period, but also how long it lasted. Finally, the time at which the initial blast overpressure reaches the corner pressure transducers is given.

8.2.2 Quasi-Static Pressure

After the initial blast overpressure, the pressure returns to near or below zero before very distinctly rising again. The beginning of this second overpressure region was chosen as the start of the quasi-static pressure region. An average is calculated for different time periods beginning with this start time; specifically, for 1 sec, 0.5 sec, 0.01 sec, and 0.05 sec. The time period must be long enough to average out the unsteadiness seen in Figure 10, however, the longer the time period, the closer to zero the value becomes because the chamber pressure is approaching atmospheric due to venting. The quasi-static pressure is directly related to the impulse, which is the integral of the time versus pressure curve.

$$P_{quasi-static} = \frac{Impulse(t_0 + \Delta t)}{\Delta t} \qquad \text{(eq 1)}$$

where:

$$Impulse(t_0 + \Delta t) = \int_{t_0}^{t_0+\Delta t} P(t)dt$$

t_o is the beginning of the quasi-static pressure region, and
Δt is either 0.05, 0.1, 0.5, or 1.0 second

From the reported results, the impulse can be easily calculated from the quasi-static pressures over consistent time periods. For example, if the quasi-static pressure over a 0.05 sec time period was 35 psi, the impulse would be approximately 1.75 psi-sec. In equation 1, the quasi-static pressure (35 psi), multiplied by the time period (0.05 sec), is approximately equal to the integral of the pressure-time curve. One example will be given in the following analysis for demonstrative purposes. For the majority of the discussion we will refer to the quasi-static pressure. Finally, as before, the time at which the quasi-static pressure region begins will be discussed.

8.3 Initial Blast Peak Overpressure

The initial blast peak overpressures for the 0.9 kg, 2.2 kg, and 3.2 kg (nominal 2 lbs, 5 lbs, and 7 lbs, respectively) TNT charges are shown in Figures 11, 12, and 13, respectively. The readings from each of the corner pressure transducers are shown as one through four. These correspond to the numbers in Figure 7. Channel "five" is the average of the readings from all four transducers. The filled symbols are from the experiments without water mist. The open symbols correspond to the experiments with water mist. Figure 12 shows the results from the repeated experiments with the 2.2 kg charge. The different experiments are noted by different symbols as shown in the legend on the graph. Note there was only one experiment with and without the water mist for the 0.9 kg and 3.2 kg charges. This convention will be consistent throughout the experimental results section. The peak pressures for the 2.2 kg and 3.2 kg charges are much higher and more scattered than the 0.9 charge. Regardless, the water mist experiments, with one exception, always show a reduction in the peak pressure.

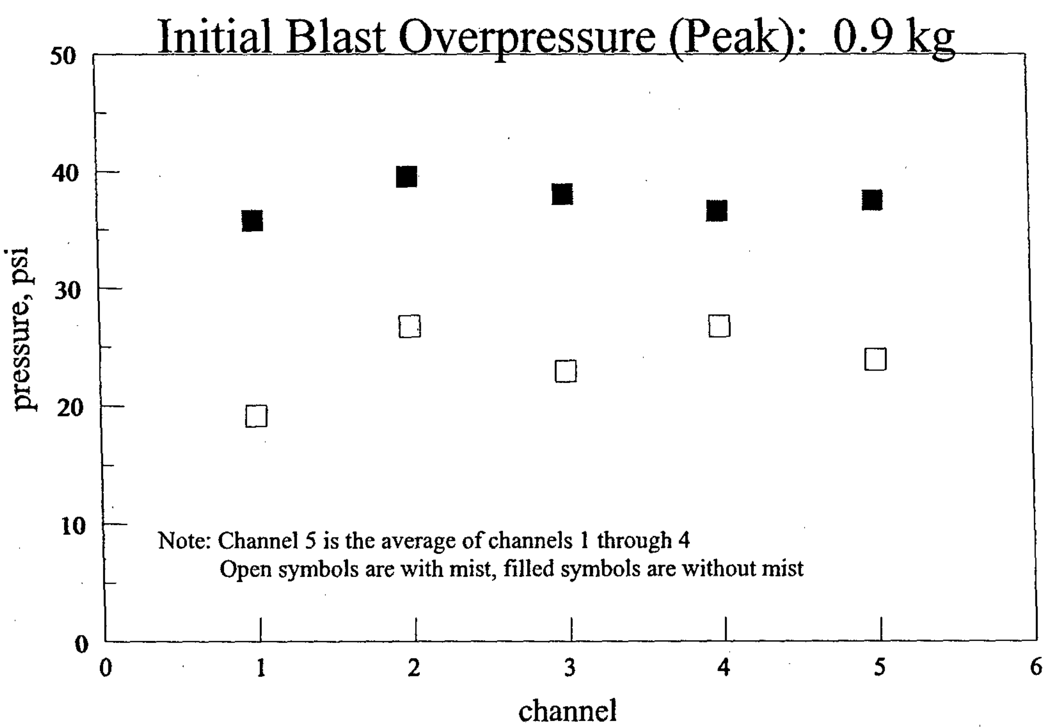

Figure 11. Initial blast peak overpressure for 0.9 kg (2 lbs) TNT charge.

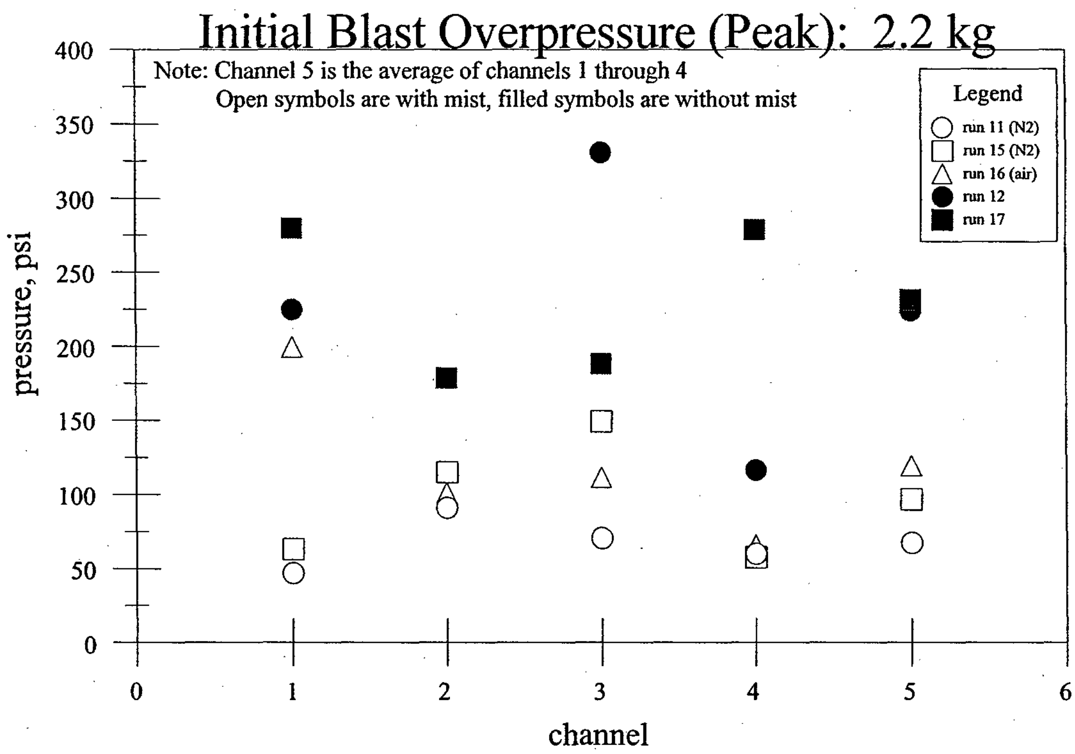

Figure 12. Initial blast peak overpressure for 2.2 kg (5 lbs) TNT charge.

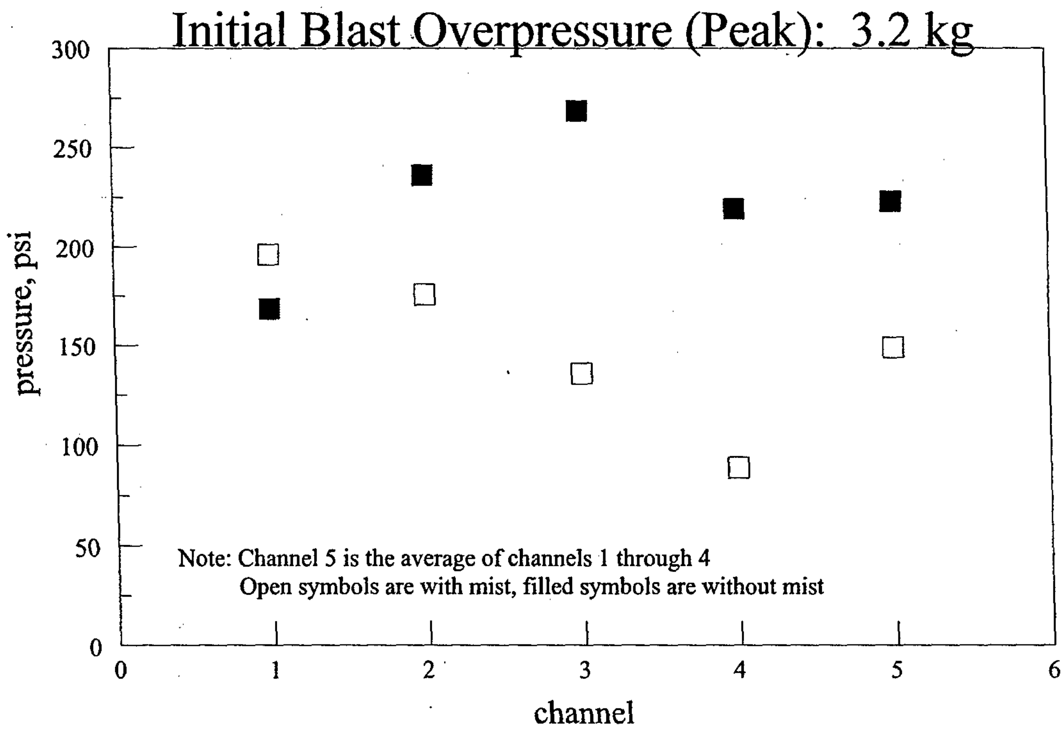

Figure 13. Initial blast peak overpressure 3.2 kg (7 lbs) TNT charge.

8.4 Initial Blast Overpressure Impulse

The impulse from the initial blast overpressure is shown in Figures 14, 15, and 16 for the 0.9 kg, 2.2 kg, and 3.2 kg charges, respectively. Note the same scale is used for the y-axis for all three graphs. The impulse increases with charge size as would be expected. There is much less scatter and the data in Figure 15 shows much better reproducibility among the repeated experiments. The presence of water mist consistently reduced the impulse regardless of charge size.

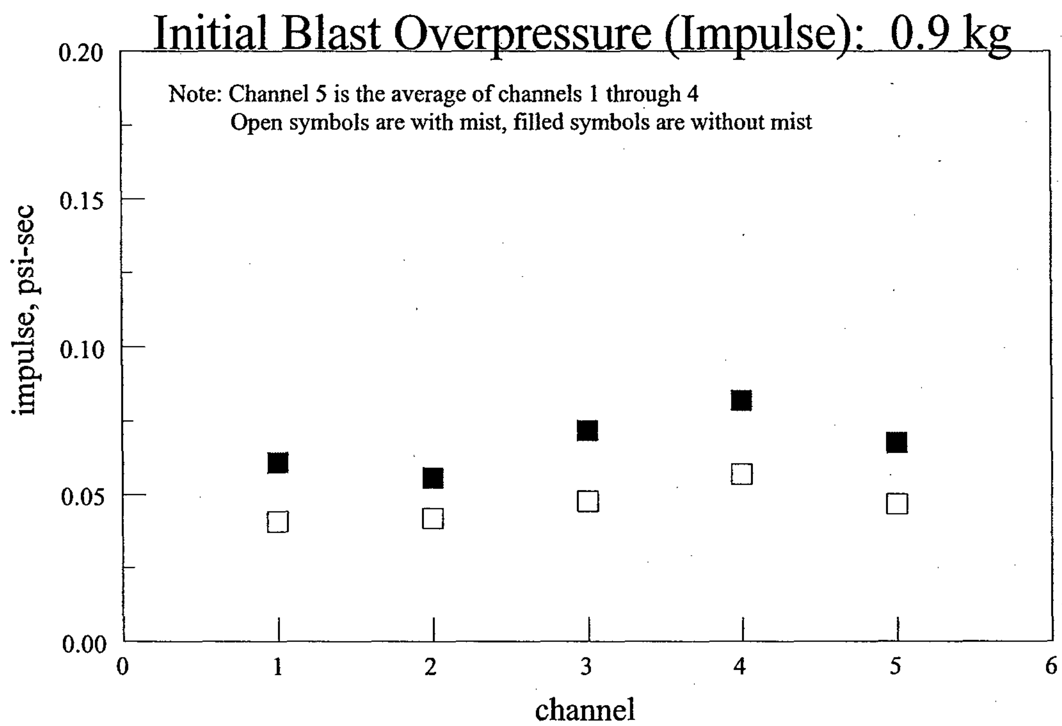

Figure 14. Initial blast overpressure impulse for 0.9 kg (2 lbs) TNT charge.

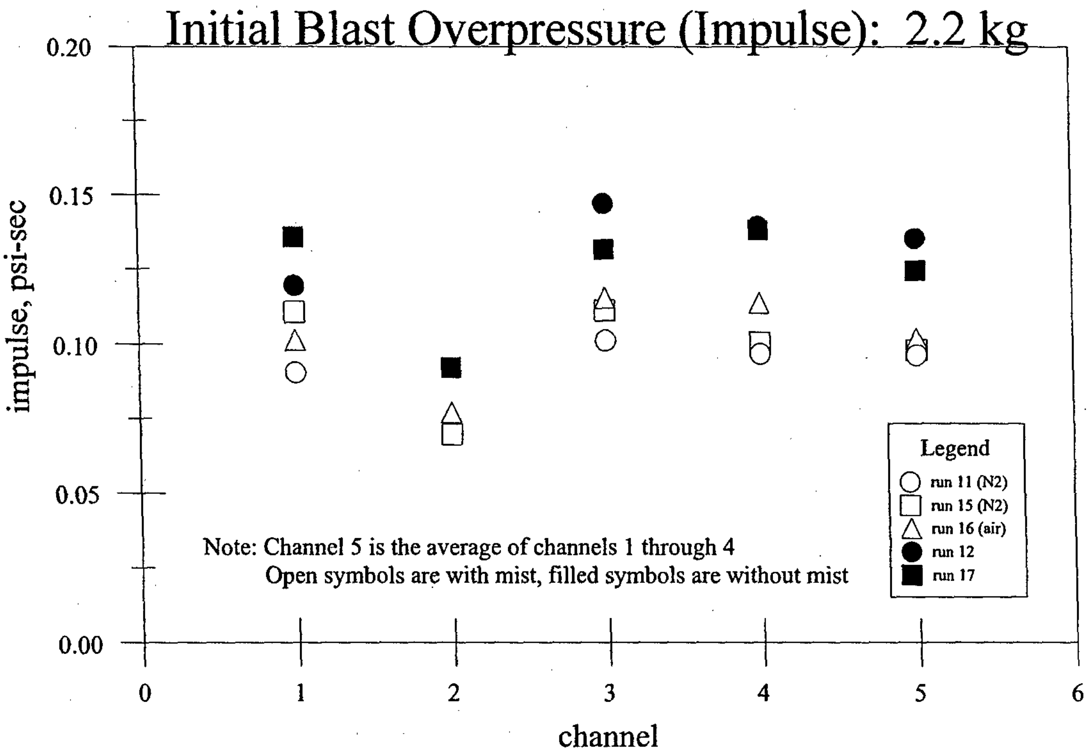

Figure 15. Initial blast overpressure impulse for 2.2 kg (5 lbs) TNT charge.

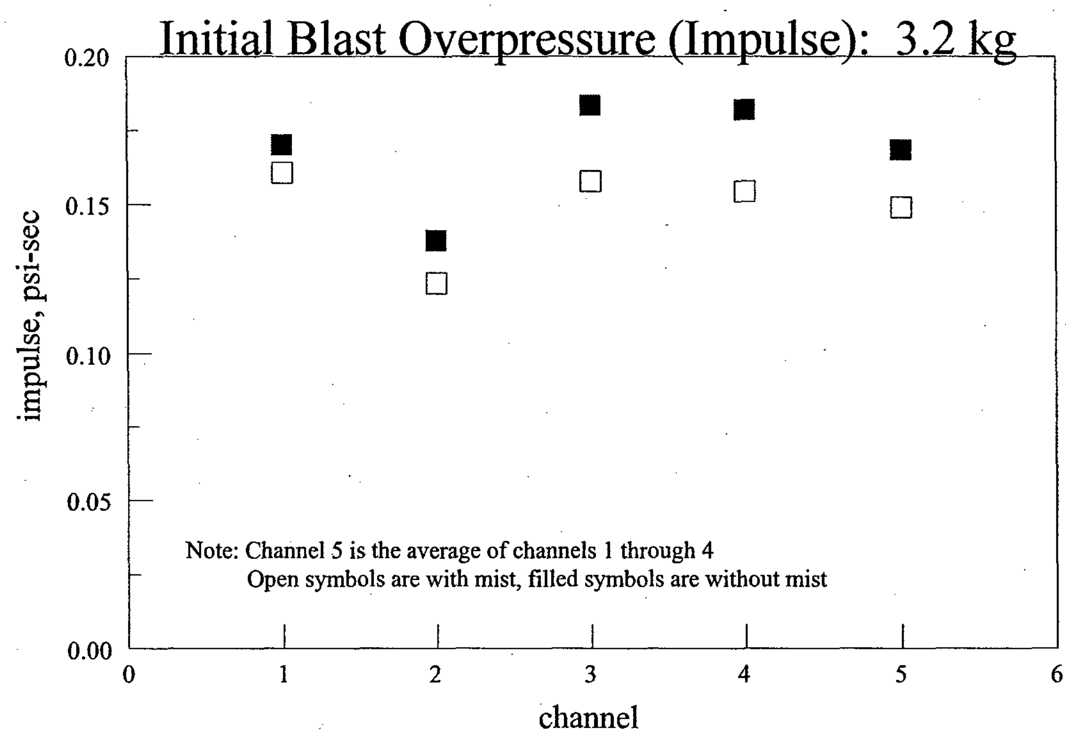

Figure 16. Initial blast overpressure impulse for 3.2 kg (7 lbs) TNT charge.

8.5 Initial Blast Overpressure Start Time

The initial blast overpressure start times are shown in Figures 17, 18 and 19 for the 0.9 kg, 2.2 kg, and 3.2 kg TNT charges, respectively. Notice again that the same scale is used for the y-axis on all three graphs. The start times decrease as the size of the charge increases. Regardless of charge size, the presence of water mist appears to delay the beginning of the initial blast overpressure waves. The delay does appear to be less for the two larger size charges. The maximum reduction in start time is never more than 0.0005 seconds.

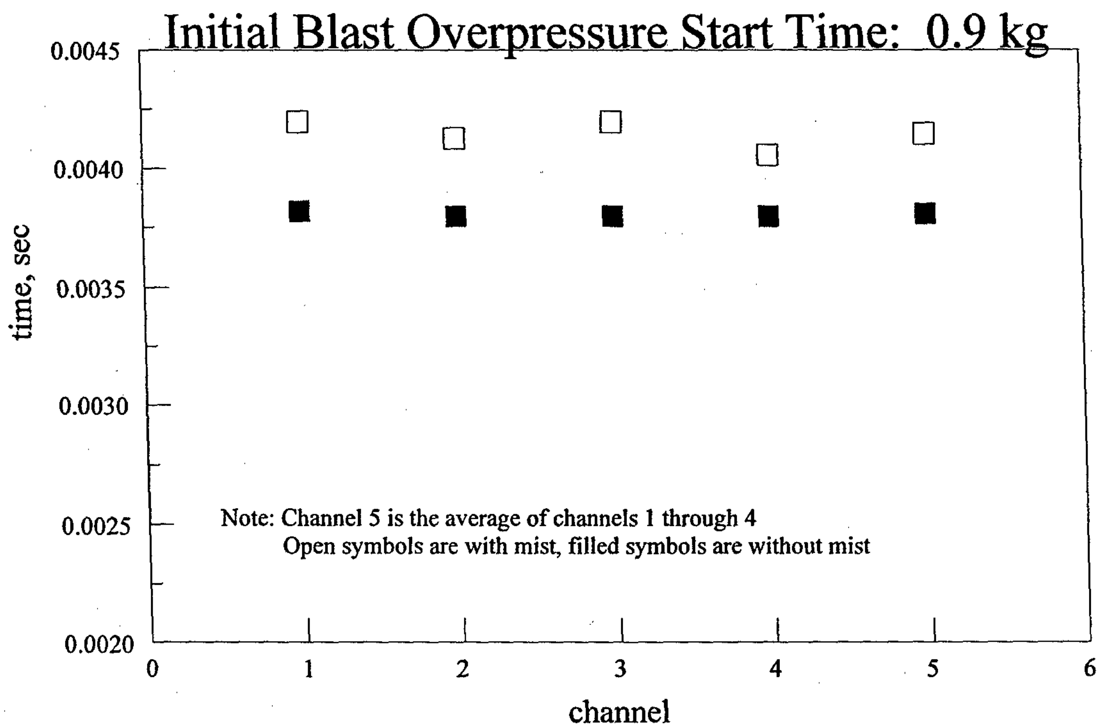

Figure 17. Initial blast overpressure start time for 0.9 kg (2 lbs) TNT charge.

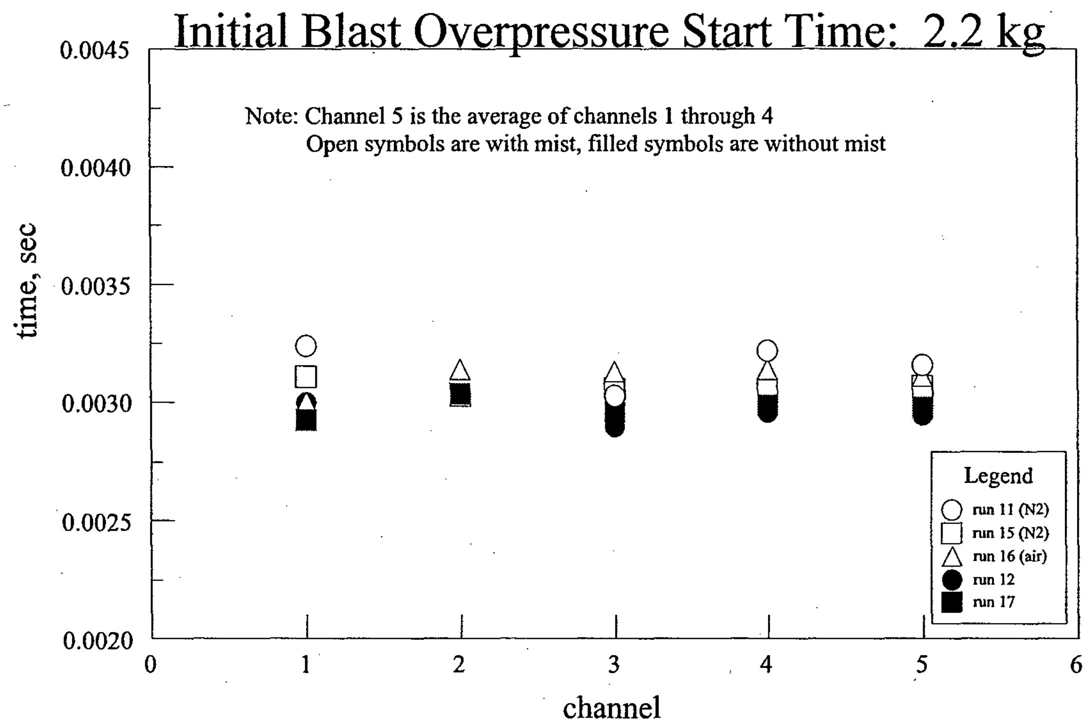

Figure 18. Initial blast overpressure start time for 2.2 kg (5 lbs) TNT charge.

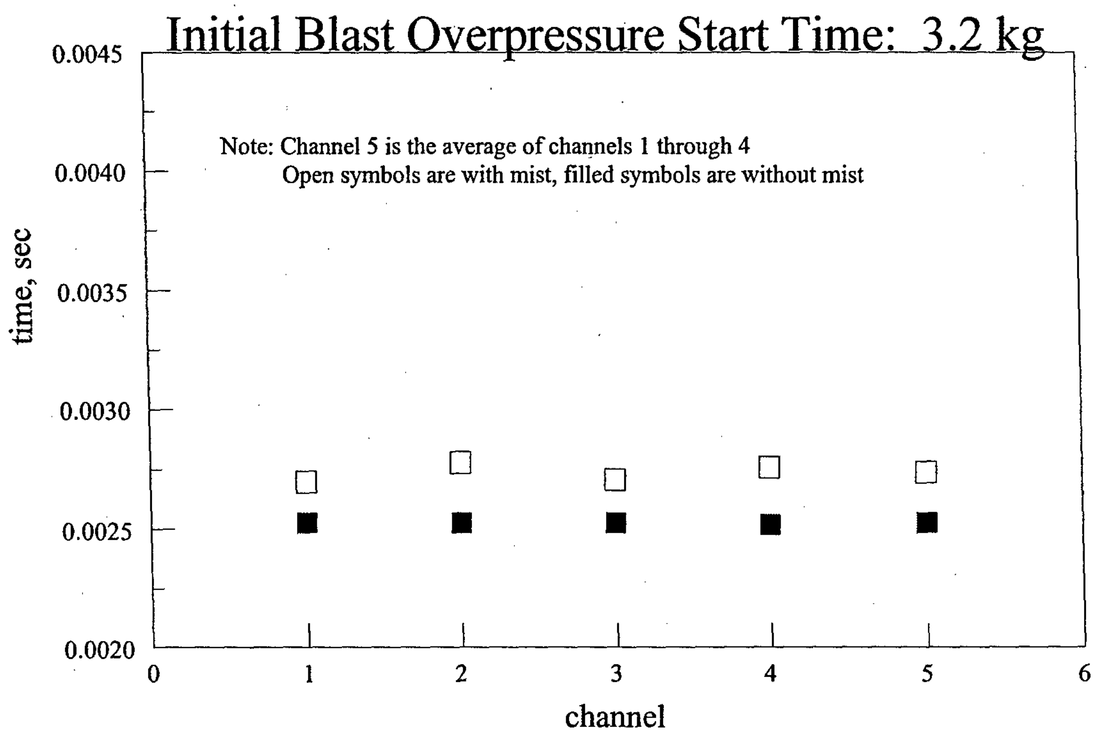

Figure 19. Initial blast overpressure start time for 3.2 kg (7 lbs) TNT charge.

8.6 Quasi-Static Pressure 0.9 kg TNT Charge

The quasi-static pressures for the 0.9 kg (2 lbs) TNT charge without water mist is shown in Figure 20. There are four data points for each channel. These represent the average of the transducer pressure readings from the start of the quasi-static region over four different time periods: 1 sec, 0.5 sec, 0.1 sec, and 0.05 sec. As mentioned above, the average pressures decrease as the length of time that the pressure is averaged over, increases. Again this is because the chamber pressure is approaching atmospheric as time passes. The quasi-static pressures for the 0.9 kg (2 lbs) TNT charge with water mist is given in Figure 21. The same trends appear, however, the pressures are lower with the presence of water mist. Figure 22 illustrates this by comparing channel "5" (the average of all four pressure transducers) for the quasi-static pressures averaged over different time periods. The reduction appears to be close to 50% at the beginning and decreases with time.

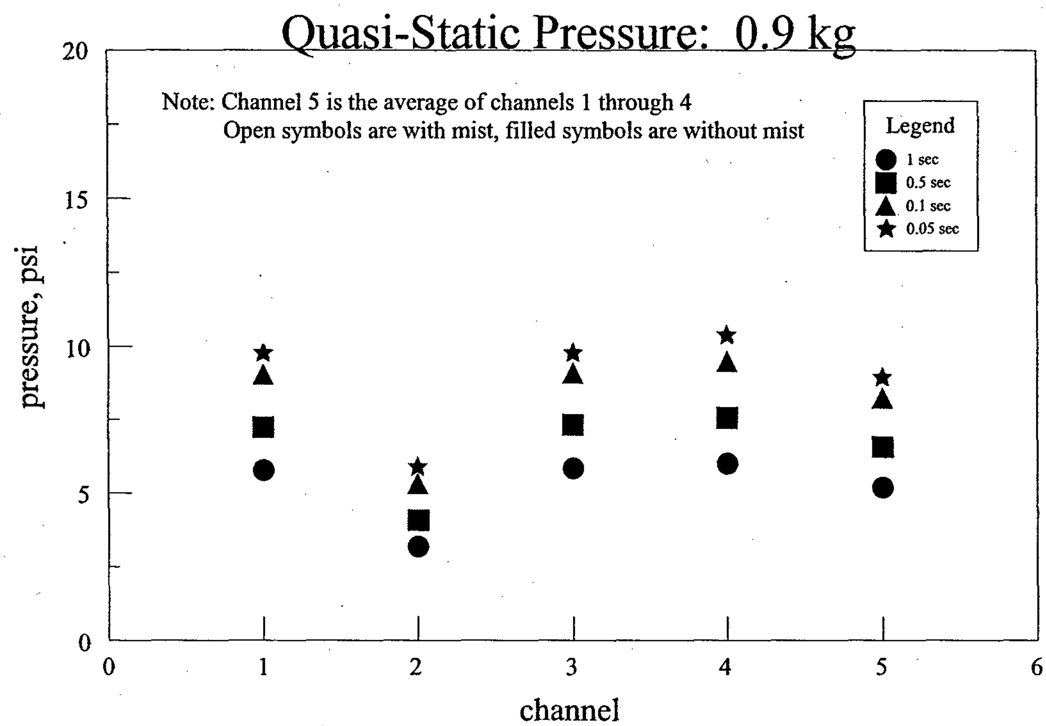

Figure 20. Quasi-static pressure for 0.9 kg (2 lbs) TNT charge without water mist.

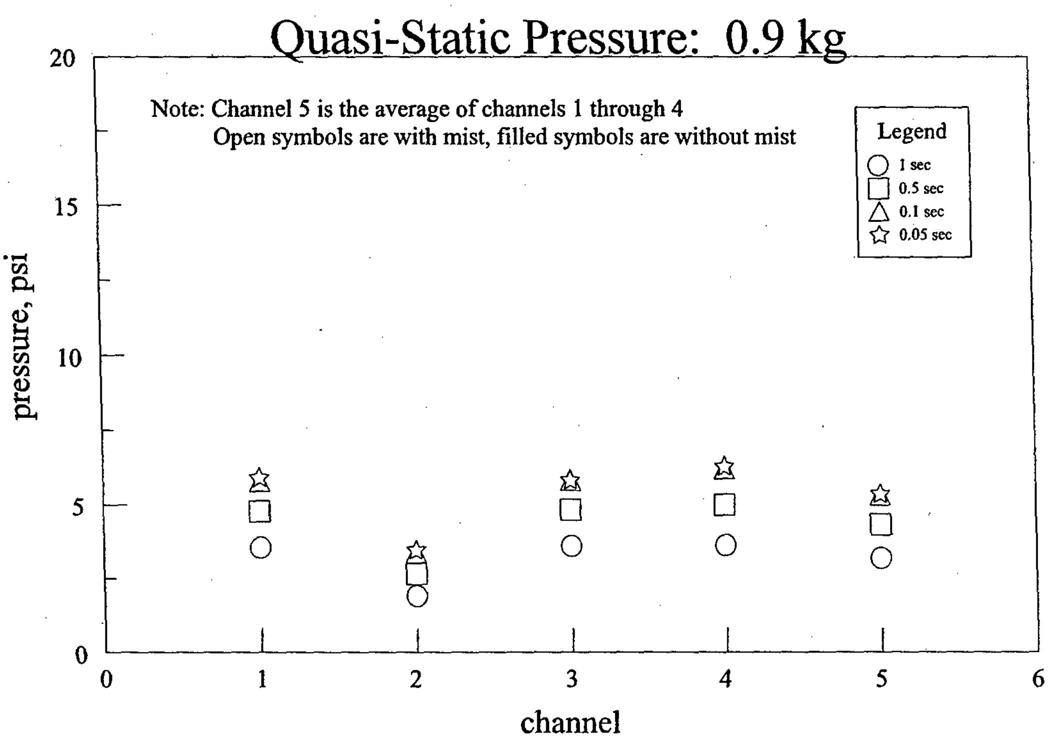

Figure 21. Quasi-static pressure for 0.9 kg (2 lbs) TNT charge with water mist.

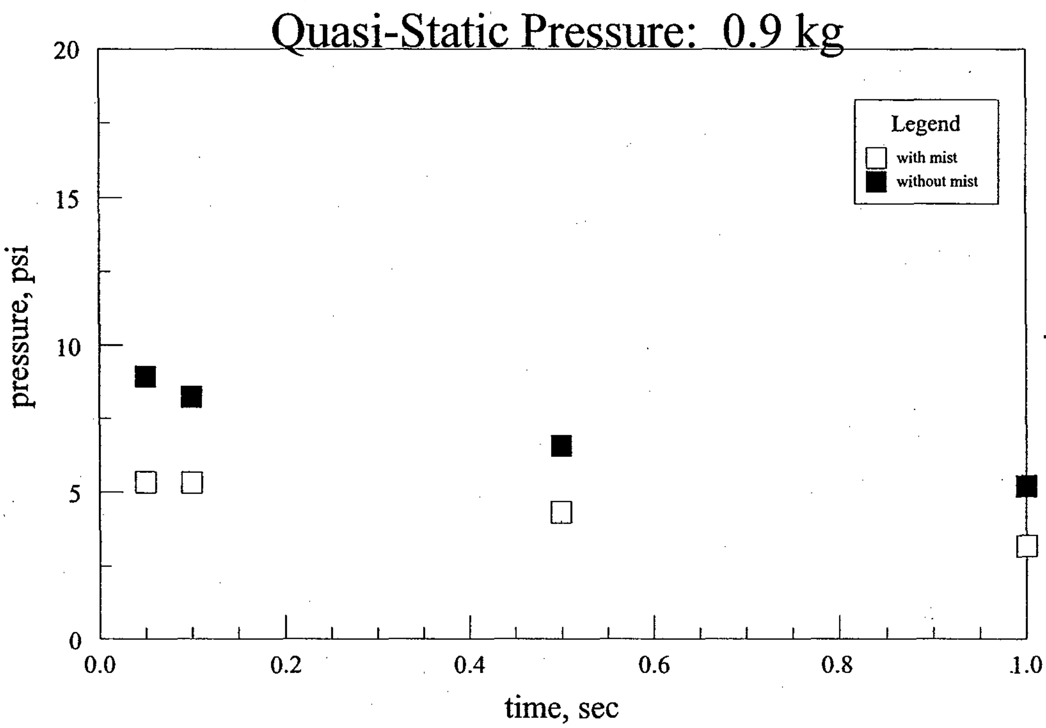

Figure 22. Quasi-static pressure for 0.9 kg (2 lbs) TNT charge.

8.7 Quasi-Static Pressure 2.2 kg TNT Charge

The quasi-static pressure averaged over a 0.05 sec time period for the 2.2 kg (5 lbs) TNT charge is shown in Figure 23. The individual runs are noted by different symbols according to the legend on the graph. Channels one through four correspond to the four high-speed pressure transducers in each corner of the bombproof chamber. Channel "five" is, as before, the average of channels one through four. Figures 24, 25, and 26 show similar data for the quasi-static pressures averaged over 0.1, 0.5, and 1.0 sec, respectively. The data shows excellent reproducibility and in all cases, the presence of water mist reduced the pressure. Figure 27 shows channel "five" for each of the four different average times. As with the smaller 0.9 kg charge, the pressures decrease as the length of time that the pressure is averaged over, increases. Unlike the smaller charge, the reduction in pressure as a result of the water mist appears to remain constant over the time periods studied so that after one second the amount that the quasi-static pressure is reduced approaches 50%.

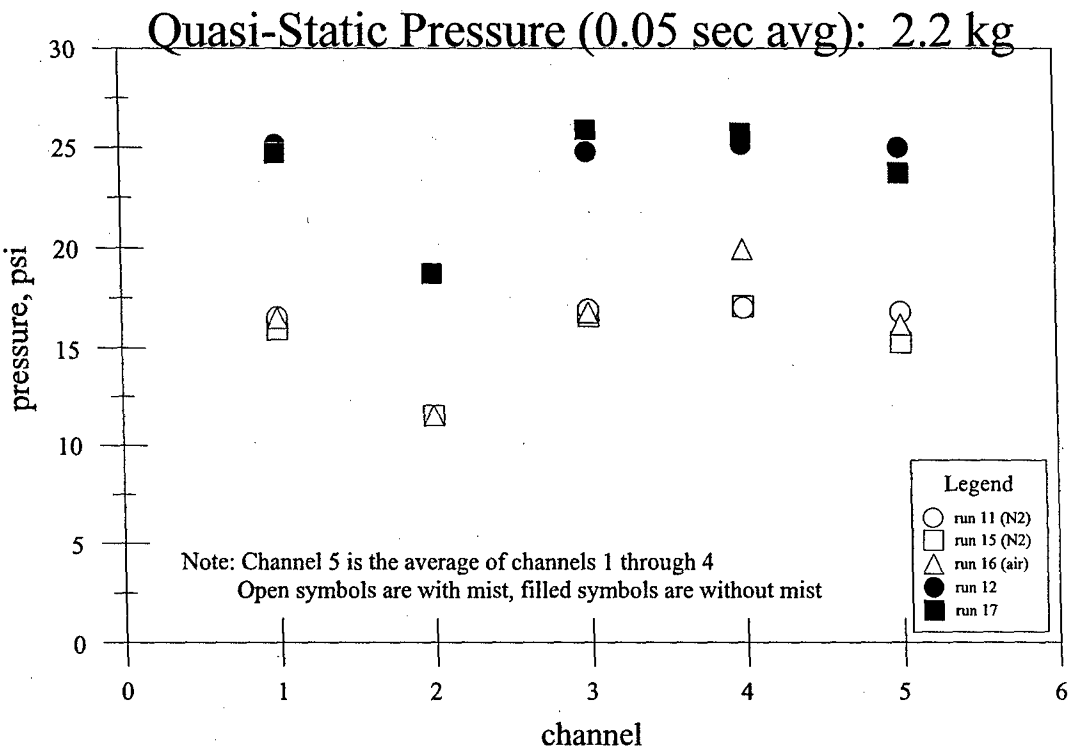

Figure 23. Quasi-static pressure averaged over 0.05 seconds for 2.2 kg (5 lbs) TNT charge.

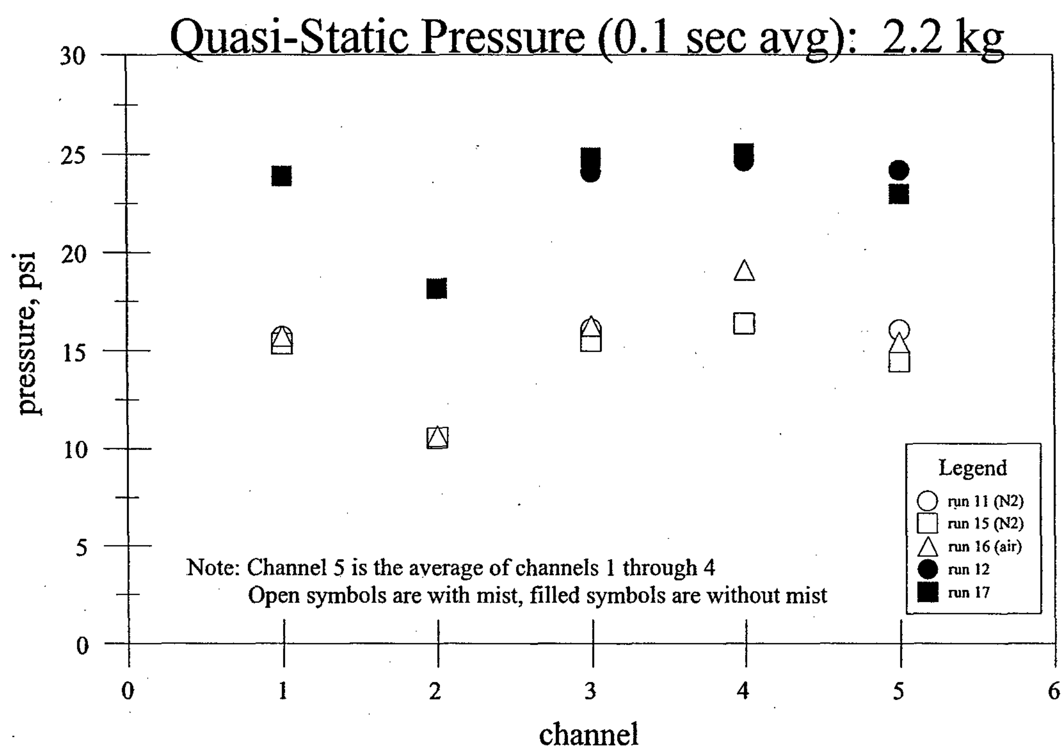

Figure 24. Quasi-static pressure averaged over 0.1 seconds for 2.2 kg (5 lbs) TNT charge.

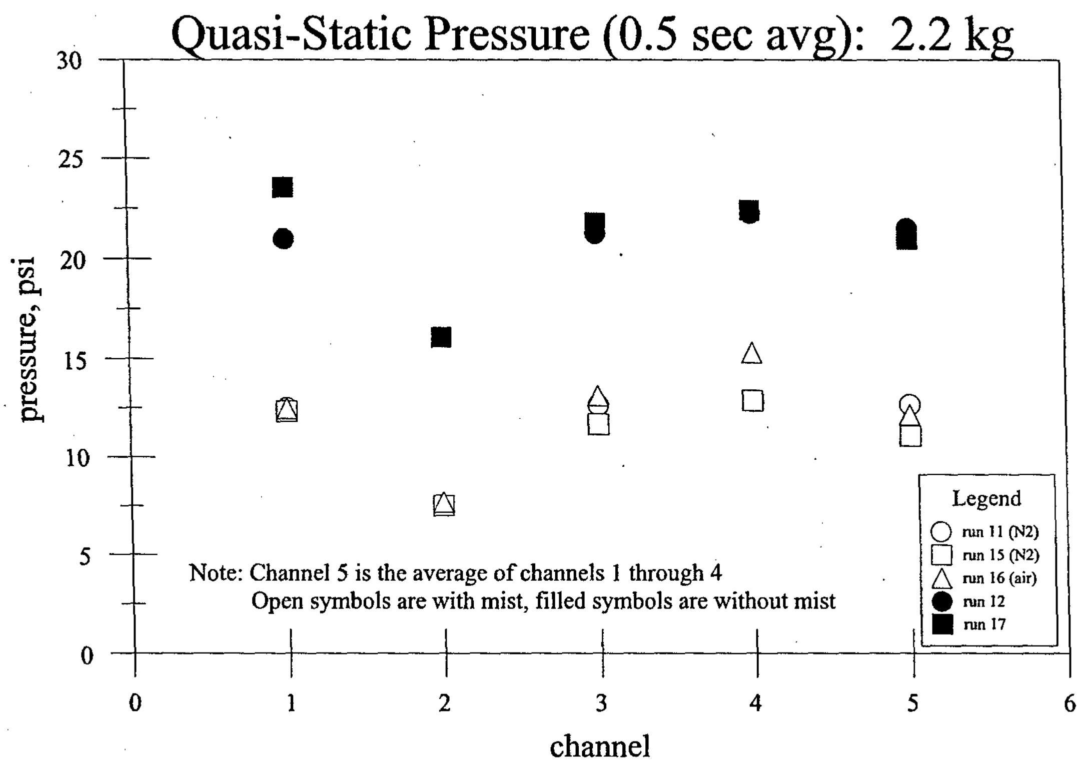

Figure 25. Quasi-static pressure averaged over 0.5 seconds for 2.2 kg (5 lbs) TNT charge.

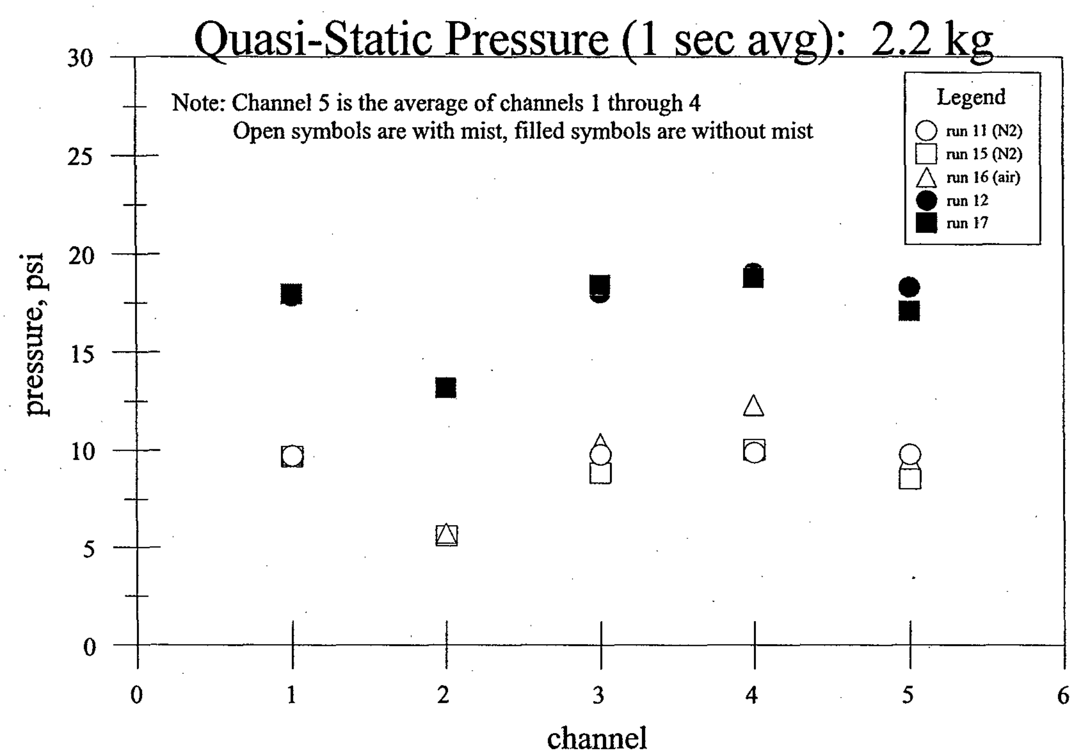

Figure 26. Quasi-static pressure averaged over 1.0 seconds for 2.2 kg (5 lbs) TNT charge.

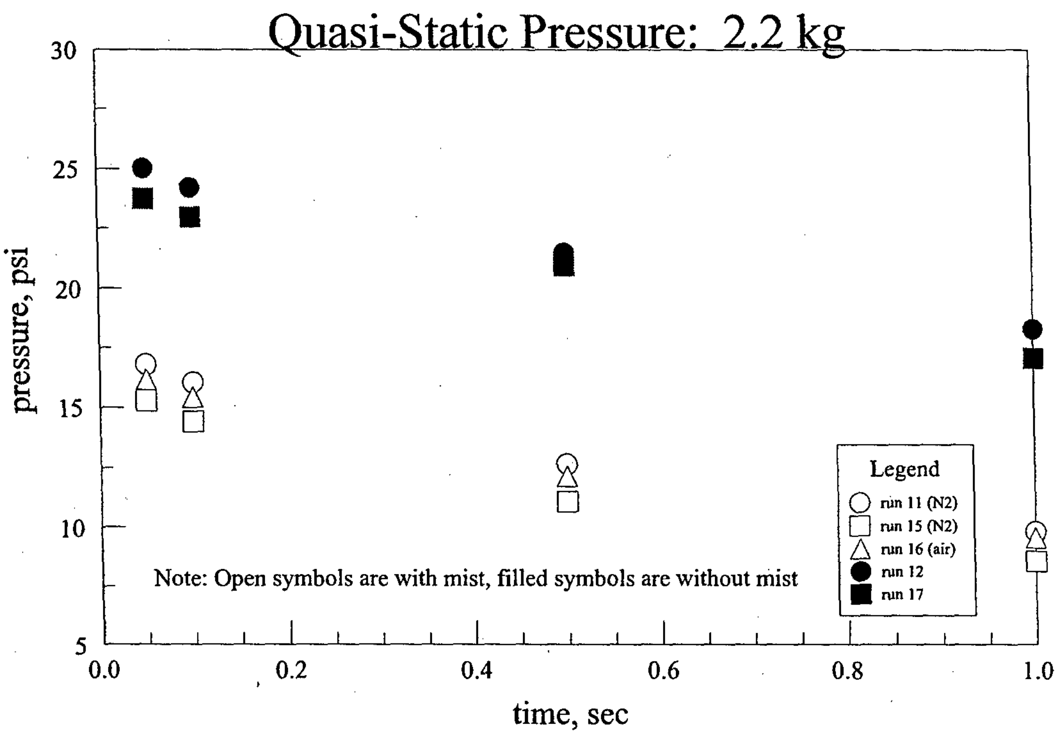

Figure 27. Quasi-static pressures for 2.2 kg (5 lbs) TNT charge.

8.8 Quasi-Static Pressure 3.2 kg TNT Charge

The quasi-static pressures averaged over the four different time periods are shown in Figure 28 for the 3.2 kg (7 lbs) TNT charge without water mist. Note that the scale for the y-axis has been increasing with charge size. Figure 29 shows the same information for the 3.2 kg (7 lbs) TNT charge experiment with water mist. Channel "five" is given in Figure 30. The presence of water mist consistently appears to have a remarkable impact on the quasi-static pressure attained within the chamber. Figure 31 shows this same data, but presented as impulse instead of quasi-static pressure. The reduction appears more extreme with a longer time period because the magnitudes of the numbers increase dramatically with time.

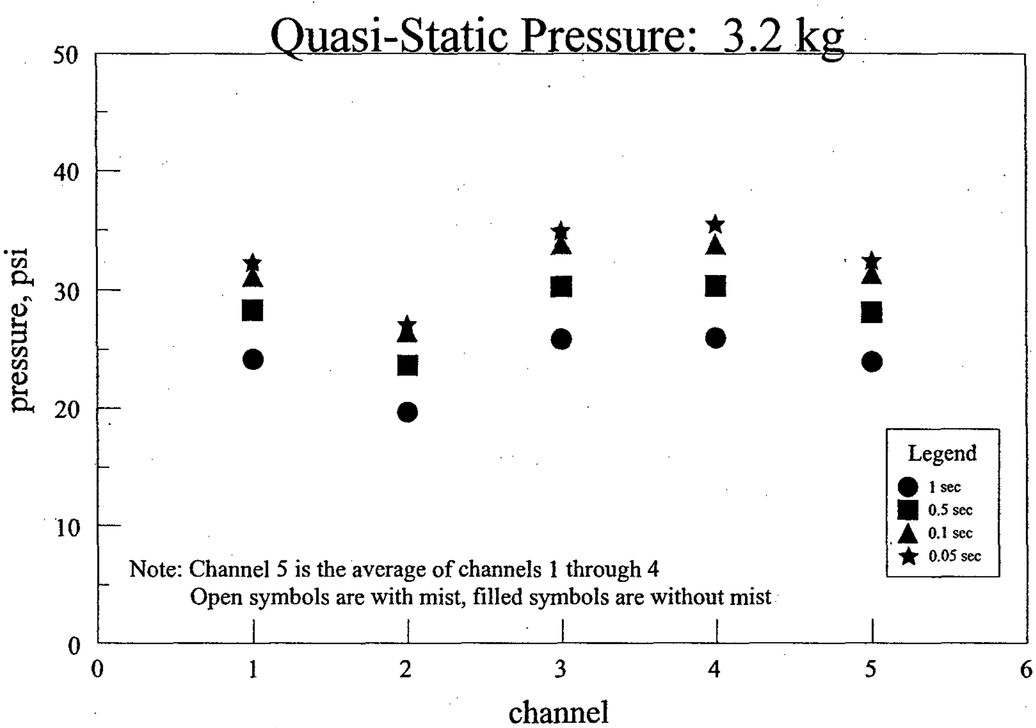

Figure 28. Quasi-static pressure for 3.2 kg (7 lbs) TNT charge without water mist.

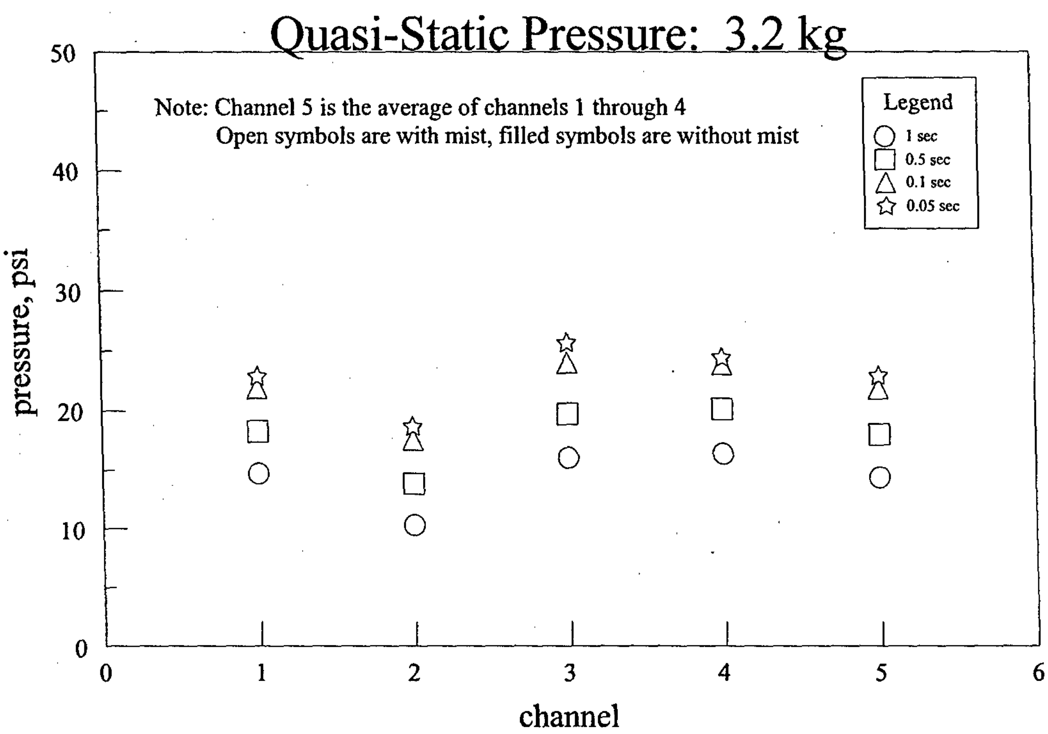

Figure 29. Quasi-static pressure for 3.2 kg (7 lbs) TNT charge with water mist.

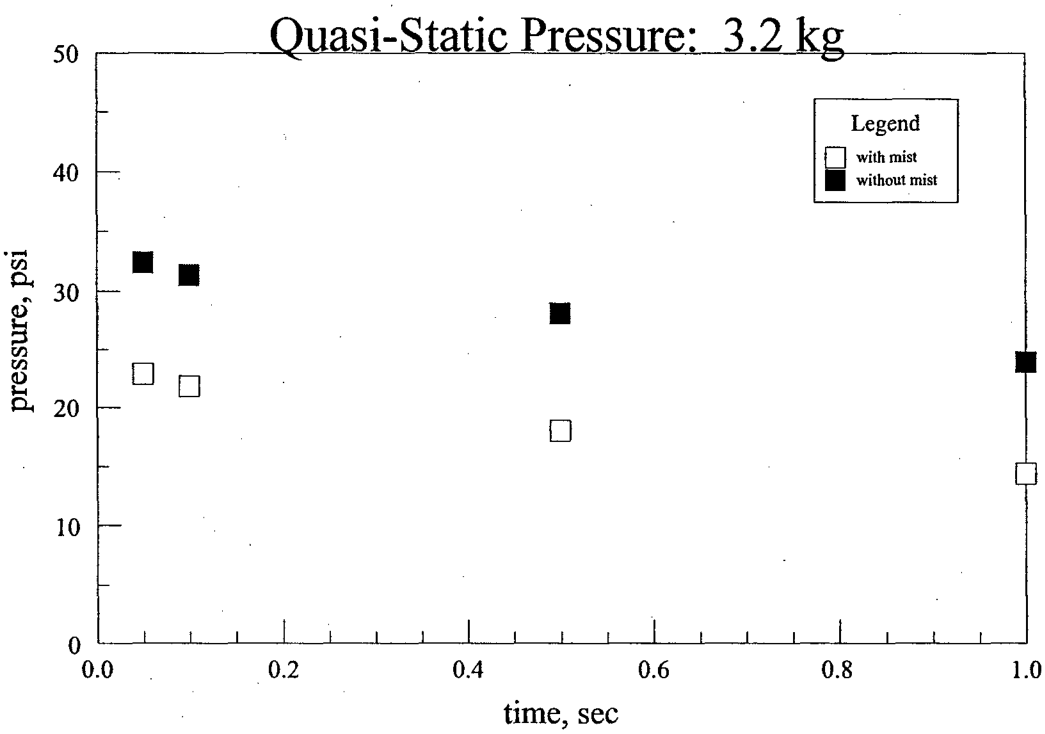

Figure 30. Quasi-static pressure for 3.2 kg (7 lbs) TNT charge.

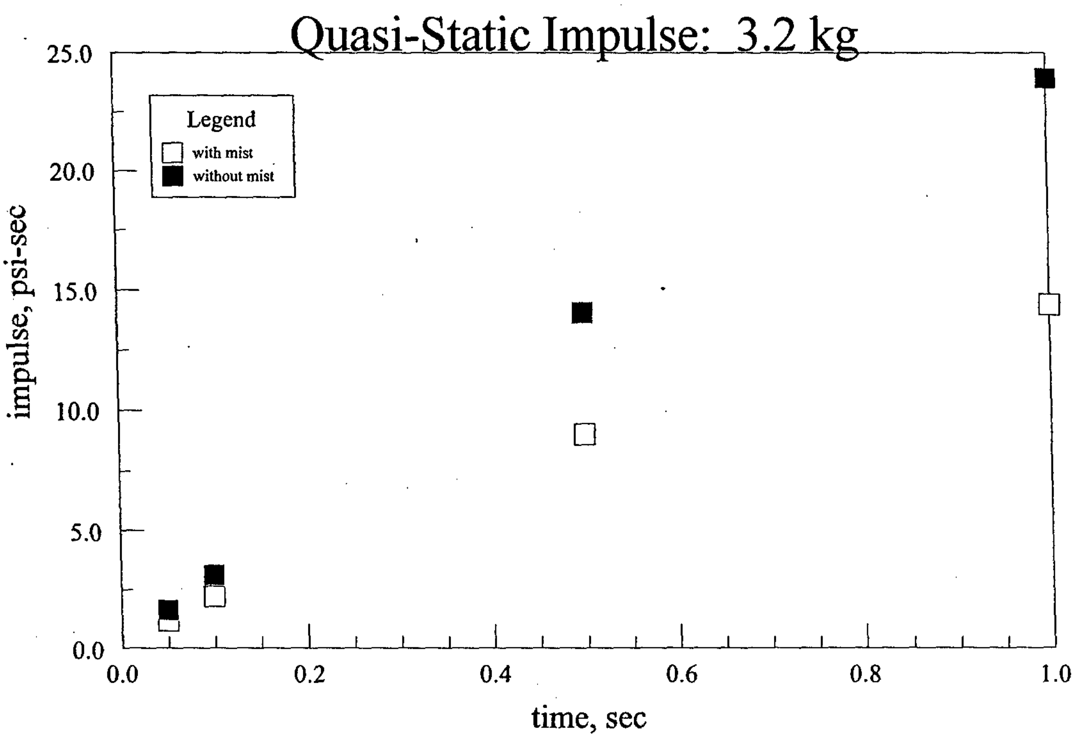

Figure 31. Quasi-static impulse for 3.2 kg (7 lbs) TNT charge.

8.9 Quasi-Static Pressure Start Time

The beginning of the quasi-static pressure start times are shown in Figures 32, 33, and 34 for the 0.9 kg, 2.2 kg, and 3.2 kg TNT charges, respectively. Notice that the start times decrease with increasing charge size. Notice also that the presence of the water mist delayed the start times by at least 0.001 seconds.

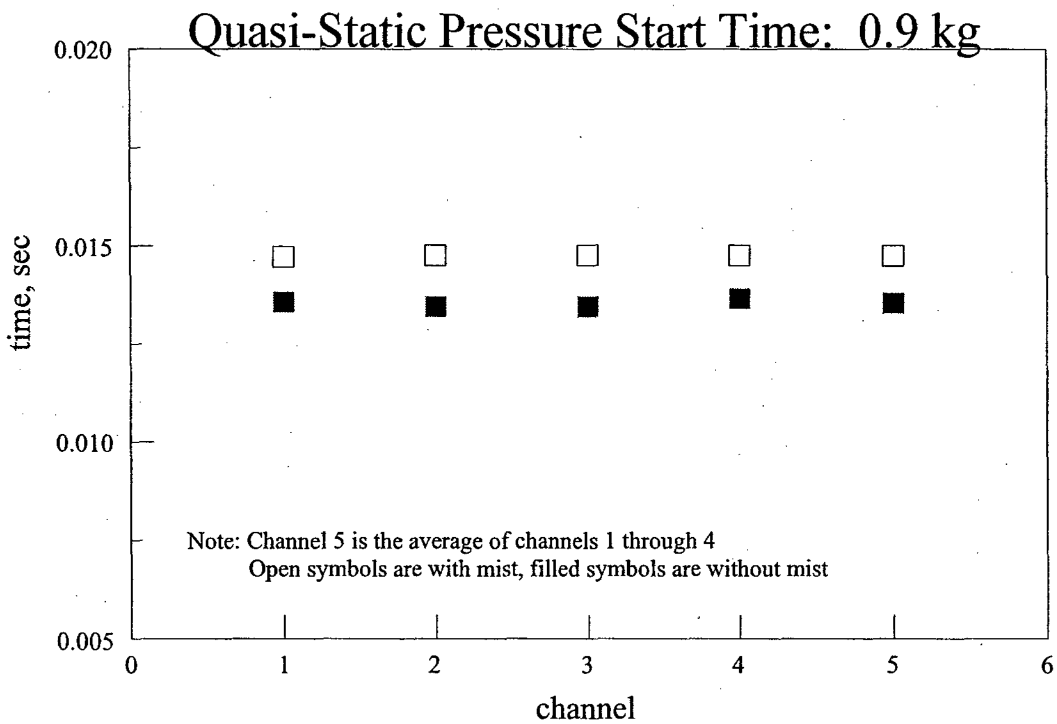

Figure 32. Quasi-static pressure start times for 0.9 kg (2 lbs) TNT charge.

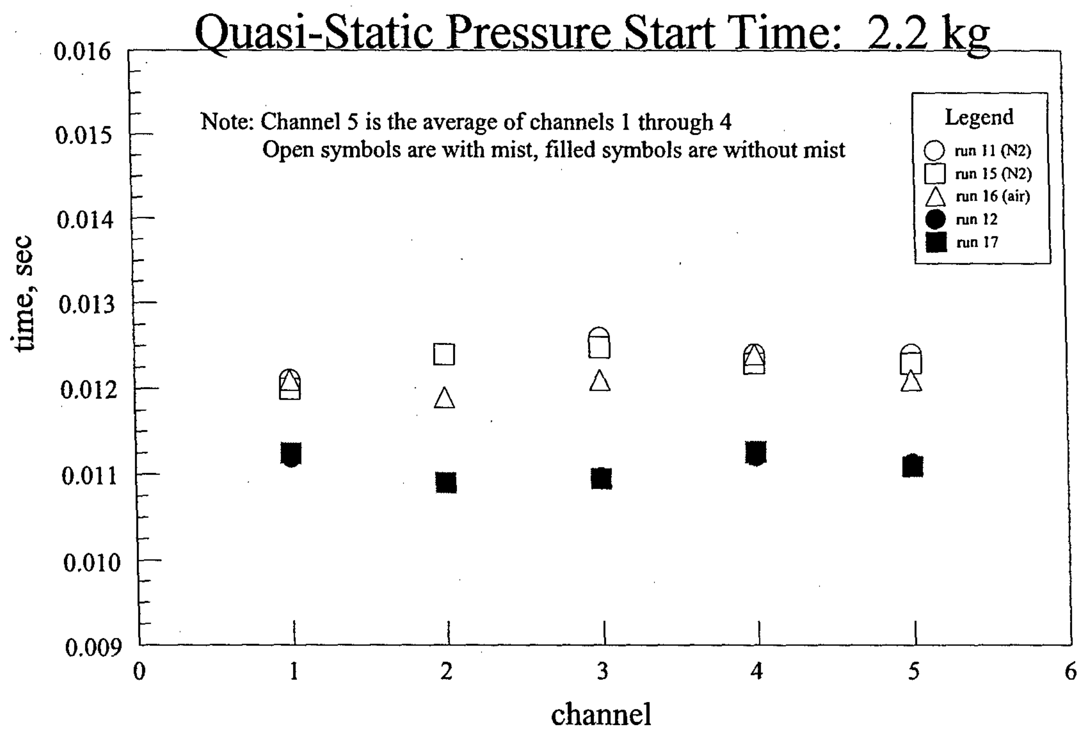

Figure 33. Quasi-static pressure start times for 2.2 kg (5 lbs) TNT charge.

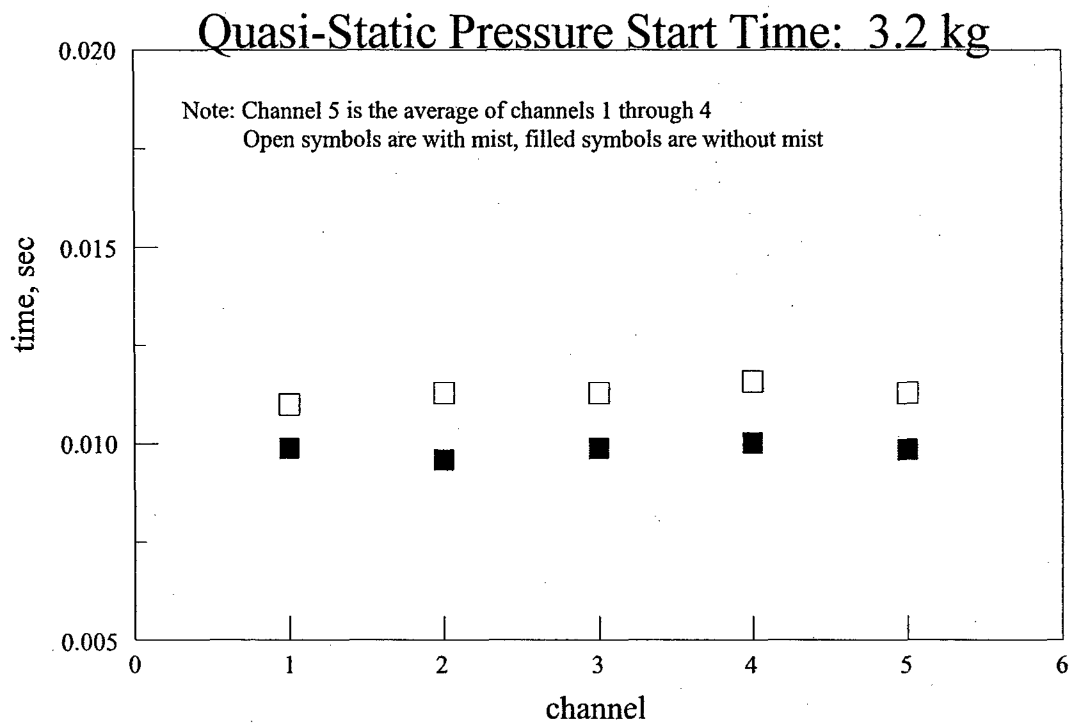

Figure 34. Quasi-static pressure start times for 3.2 kg (7 lbs) TNT charge.

9.0 CONCLUSIONS

A series of experiments demonstrating the mitigating effect of water mist on the overpressure effects of a TNT detonation has been completed. A water mist system was designed and installed in a bombproof chamber located at the Naval Surface Warfare Center, Indian Head, Maryland. A series of TNT charges, 0.9 kg (2 lbs), 2.2 kg (5 lbs), and 3.2 kg (7 lbs), were detonated both with and without employing the water mist system. The TNT detonations were characterized by five measurements: initial blast overpressure start time, peak, and impulse; quasi-static pressure and start time. The initial blast overpressure peak and impulse, as well as quasi-static pressure, were always reduced (with one minor exception) by the presence of water mist. The quasi-static pressure, averaged over one second, was reduced by 40%, 47%, and 40% for the 0.9 kg, 2.2 kg, and 3.2 kg charges, respectively. In addition, both the start of the initial blast overpressure and quasi-static pressures were delayed. These experiments show that the use of water mist to mitigate the overpressure effects of a high

explosive detonation is an extremely promising concept. Future blast mitigation experiments will encompass 22.7 kg (50 lbs) TNT test charges and continue with predictive model development and validation.

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